Digital Analytics and Robotics for Sustainable Forestry

CL4-2021-DIGITAL-EMERGING-01

Grant agreement no: 101070405

DELIVERABLE 6.1

Title of Deliverable

Due date: month 3 (November 2022)
Deliverable type: R
Lead beneficiary: WSL

Dissemination Level: PUBLIC

Main author: Holger Griess, Janine Schweier

1 Part A: Documentation of forest training provided

WSL organised a forestry workshop on 1st and 2nd of September 2022, entitled "Forestry for non-foresters" aiming to bring together the different disciplines that are needed to develop high quality forestry Decision Support Systems. It is important that a common understanding exists of what forestry is and which aspects are of relevance for different stakeholders when mobile autonomy, forest mapping, data analytics and autonomous logging are envisaged. Therefore, 30 participants from different disciplines attended the workshop that was held in the Rameren test site located next to the WSL facility. WSL's organisers, Holger Griess and Janine Schweier, guided the participants through the forest and showed and discussed different forest images. The topics included various aspects from forest inventory, -planning and -management, fostering of biodiversity and provision of forest ecosystem services, to the consequences of extreme disturbances and the international timber market (more information is given below). All aspects were discussed from the (Swiss) Central European as well as from the (Finnish) Nordic perspective. Whenever possible, a link to the Digiforest project was shown and discussed (e.g. shape of stem is important for foresters because of the economic value => important label to collect).

1.1 Stations and content of discussion during the field trip

1.1.0.1 Forestry in general

- What does forests need (water, nutrients, etc.) to grow?
- What does forests provide to the society (biodiversity and ecosystem services)?

Figure 1: Forestry in general: what is it for, how does it work and what does the forest need? (WSL)

1.1.0.2 Soil profile

- Why are forest soils so unique (-> undisturbed)?

- Why are nutrients important and where are they located?
- What are forest roads and skid trails and what happens if forest machines drive on the surface (under different weather conditions)?
- Why are soils challenging?
- What do we do to preserve the forest soils?

Figure 2: Information about forest soils. Why are they unique and what is done to avoid damage? (WSL)

1.1.0.3 A "normal" forest stand

- Social structure of forests
- Mixtures of species
- Importance of biodiversity
- Provision of ecosystem services
- Forest growth, etc.
- Important parameters from foresters‘ perspective, such as crown, proportion of crown to height, knot-free trunk
- Link to the Digiforest project (e.g. use LiDAR to see how wide the crown is).

1.1.0.4 Silvicultural measures

- Usage of the given example to discuss management forms (e.g. rotation forestry, continuous cover forestry) -> The form of management influences various criteria (e.g. quality, height, vitality)

Figure 3: Discussion in a "normal" forest stand (WSL).

- What are management aims of foresters/forest enterprises?
- Discussion of management challenges, advantages and disadvantages
- Demonstration/exercise of future crop-tree selection (=showing which trees represent different management aims)
- Discussion how forest inventory and forest planning works.

Figure 4: Thinning and other silvicultural measures.

1.1.0.5 Storms and other unplanned disturbances

- From thinning to storm wood

- In case of disturbances, it cannot be harvest much of the planned volume (of the entire rotation period)
- Today, it is known that one has to shorten rotation times -> it has to be managed differently and faster
- Discussion about the economic dimension of extremes.

1.1.0.6 Meeting with forest practitioner

- The local forester of the Swiss case study site in the canton Schaffhausen was met
- He gave information about the forest enterprise in general and more specific about the test site and explained which variables are of high importance for forest planning from his viewpoint.
- Participants had the possibility to ask questions and a discussion developed.

Figure 5: Exchange with the forester of the Swiss case study site in the canton Schaffhausen (Schweier/WSL, left and Bose/WSL, right)

2 Part B: Forestry in a nutshell

In the following section, above-mentioned parameters are explained more detailed. This allows other project collaborators who will eventually join the project later as well as other researchers outside Digiforest working on this interface to link the different disciplines.

2.1 Forestry in general

Forestry is rooted in the basic sciences of biology, chemistry and mathematics and is performed with the applied sciences of ecology, silviculture, and management. While science guides the decisions of a forester, it does not make them for him or her. Foresters must apply their knowledge in a decision-making arena where good solutions are not always obvious, conflicting human interests must be considered, and conflicting opinions must be compromised. This need for experienced judgment, diplomacy and tact constitutes the art of forestry.

In addition to timber production, sustainable forest management also includes the promotion of biodiversity and the provision of a variety of important ecosystem services such as recreation, protection against gravitational natural hazards and carbon storage.

Which of these services is targeted depends on the operational objectives; for example, a forest close to an urban area may emphasize recreation or, where necessary, protective functions, while a public forest tends to promote biodiversity and a privately owned forest economic aspects. One often finds a mixture of several objectives. The central task of forest planning and management is to ensure the sustainable provision of these envisaged ecosystem services.

2.2 Forest soils

2.2.1 Context

Through clever interventions, we can ensure the useful, protective, and recreational functions of our forests sustainably and in the long term. Today's technologies with which these interventions are carried out are highly productive. However, this advantage can only be realised in combination with adapted development and its optimal use. Good forest road access and a strip road network are ensuring that all necessary measures for sustainable management can be carried out.

The Nordic countries usually are managed using forest strip roads being established every 20 m to make stands accessible for harvesters with a reach of 10 m. Central Europe‘s forests are managed using forest strip roads with 20- to 40-m distance between them, and with restrictions limiting access for any machine in the matrix between the strip roads. This distinction is important to know and understand when any harvesting operations in these countries is discussed and machines are developed.

2.2.2 Consequences of soil compaction

Our forest soils are a complex three-phase system consisting of air, water, and solid matter. Under the influence of the factors parent material, climate, relief, activity of soil flora and fauna, a site-typical soil structure develops. This has a considerable influence on the quantity and form of soil pores and thus on the water and air balance as well as the growth conditions for plants. The more stable this structure is, the lower the risk of soil damage by forestry machinery. When forestry machines are used improperly, the natural structure is altered by shearing of the soil due to slippage of the tyres, and the compaction by the contact surface pressure. This phenomenon is strongly impacted by the weather conditions: the wetter it is, the heavier is the impact (Figure 6). Compaction can lead to elastic deformation (=track type 1, Figure 7), plastic deformation (=track type 2, Figure 7), or viscous-plastic deformation (=track type 3, Figure 7), which impacts soil functions in a long term.

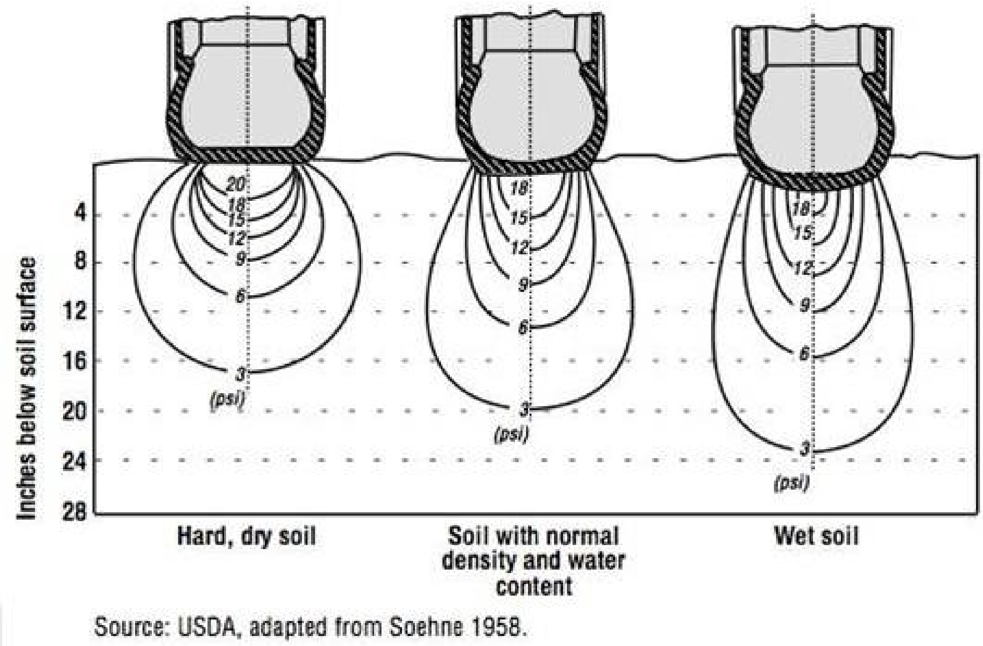

Figure 6: The effect of soil moisture on pressure distribution.

Soil compaction occurs when soil particles are reoriented more tightly to counter the load at the expense of pore space (Figure 6). In addition, the shear forces of the wheels and tracks of the forestry machines acting parallel to the soil surface cause a reduction in water and air permeability in the remaining pores. If the soil structure is damaged, important soil functions can be negatively affected, such as regulatory functions and the habitat suitability for certain species. The effects of compaction can lead to reduced oxygen availability, increased surface water runoff, and increased sedimentation. Ultimately, these negative impacts can hinder root and tree growth and negatively affect the productivity of the site.

To summarize, **damage to the soil should be avoided**. It can occur if ground pressure and load bearing capacity are not in balance. The following major factors influence this balance:

- machine weight (static/dynamic)
- pressure exerted into soil by drive system
  - static/ dynamic
  - area
- water content of soil.

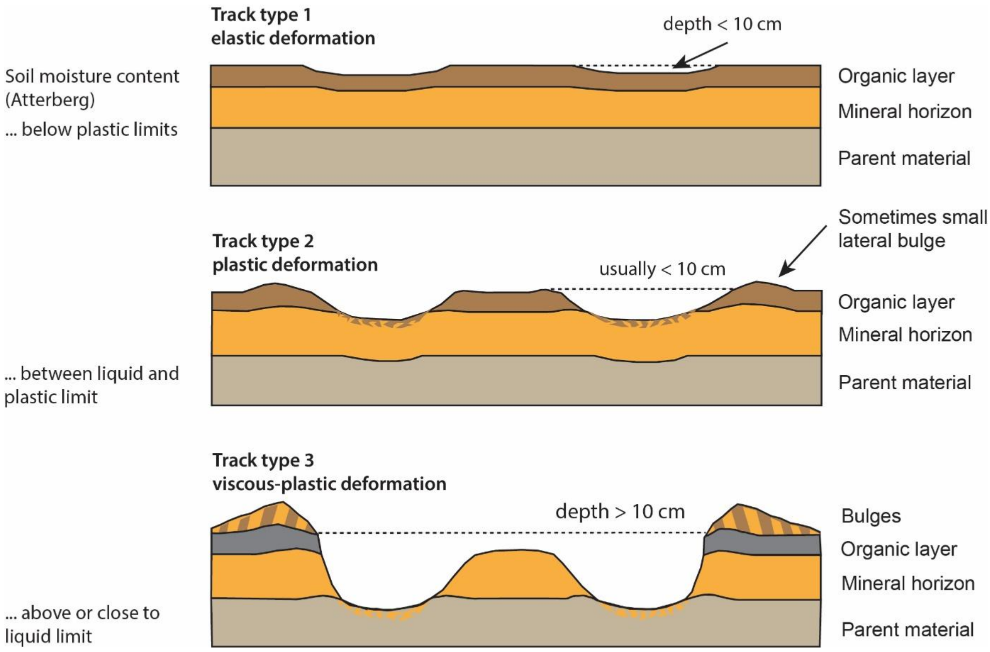

Figure 7: Visual typing of the tracks by type of changes in the soil (Lüscher et al. [3]).

2.2.3 Regeneration of compacted forest areas

Whether and how well a soil can recover from driving damage depends on the activity of the soil flora and fauna and the severity of the damage. A good indication of soil activity is the humus form. Active soils have the humus form gauze, less active mould and soils with low biological activity have the humus form raw humus. In the case of track types 1 and 2 (Figure 7)) and a mull, the prospects of the soil recovering can be considered good. With track type 3 (Figure 7)), no improvement of the condition occurs, regardless of the humus form. Soil compaction, analogous to track type 3, which was caused by wagon trains during the settlement of the western USA, can still be demonstrated today.

Technical methods such as ploughing are out of the question for loosening compaction because they damage the roots and additionally mix the soil, thus changing the natural bearing of the forest soil. There are also attempts to reduce soil compaction through biological measures. For this purpose, tree species with high root energy such as willows and alders have been planted in the track. Although a long-term result is still pending, it was found as an interim result that this procedure does not lead to the desired success if there is too much shade under canopy.

2.2.4 Legal requirement

These kind of impacts or damages reduce the natural fertility of the soil, which must be preserved by law (cf. Swiss Federal Law on the Protection of the Environment). According to Art. 1, impacts that could become harmful or a nuisance must be limited at an early stage as a precautionary measure. A soil is considered fertile if "it has a species rich, biologically active biocoenosis typical of its location and a typical soil structure as well as undisturbed decomposability; natural and man-influenced plants and plant communities can grow and develop undisturbed and their characteristic properties are not impaired; and the plant products are of good quality and do not endanger human and animal health" (see Ordinance on Soil Pollution (VBBo), Art. 2). Furthermore, Art. 6 of the Ordinance states that "whoever (...) manages the soil must, taking into account the physical properties and moisture of the soil, select and use vehicles, machines and equipment in such a way that compaction of the soil, which endangers soil fertility in the long term, is avoided" (VBBo, Art. 6). Crucial in the context of timber harvesting is the reference to the long term, because in the case of unfavourable weather conditions and improper execution, even a single driving operation can lead to long-term impairments of the soil structure.

2.2.5 Responsibility

In Switzerland, every actor in forestry bears responsibility and can contribute to soil protection (Lüscher et al. [3]). By law, the forest owner is responsible for the protection of the forest soil. In the public forest, a forest enterprise usually takes over forest management and the management is responsible for careful planning and implementation or, if a logging operation is awarded, is also responsible for the acceptance. A central person in the implementation of soil protection is the machine operator, who determines during the work whether gentle driving is possible. The cantonal forestry service influences compliance with soil protection requirements as part of its sovereign function and its advisory and training activities. As the competent enforcement body, the Swiss Soil Protection Agency is responsible for compliance with the legally stipulated requirements and is the contact for questions in this regard. These tasks can be delegated to the forest service.

2.2.6 Measures and working practices to reduce soil compaction

Specific measures such as planning of the forest access, time planning and mapping of soil types/species can avoid soil damage or at least reduce impacts to forest soils. The latter point, mapping of soil types/species, might be of special relevance in the frame of the Digiforest project: The risk of soil changes due to driving varies for different soil types and their water content. With an area-wide mapping of soil types, the fine development could be divided into different damage risk classes. These would allow, for example, to give preference to high-risk soils in the event of unfavourable weather forecasts and then, in the event of increased soil water content, to switch to zones with a low risk of damage, or to specify a maximum permissible contact surface pressure in an invitation to tender (Figure 8).

Beside planning aspects, appropriate technology can be applied to reduce soil compaction, such as:

- **Making use of small-scale machinery.**
- **Lowering the tyre pressure** to increase the contact area between the wheel and the ground and to reduce slippage when driving.
- **Using of bogie tracks** to improve traction, gradeability and downhill safety. They have proven their worth in practice because the traction forces are transmitted to the ground with less slip and thus track formation can be significantly reduced.
- **Using brushwood mats** (in fully mechanised conifer harvesting), that are laid down on the skid trails to protect the ground, especially during the following skidding. The traction forces when driving are thus transferred to the brushwood mat and not directly to the ground, which considerably reduces tracking.

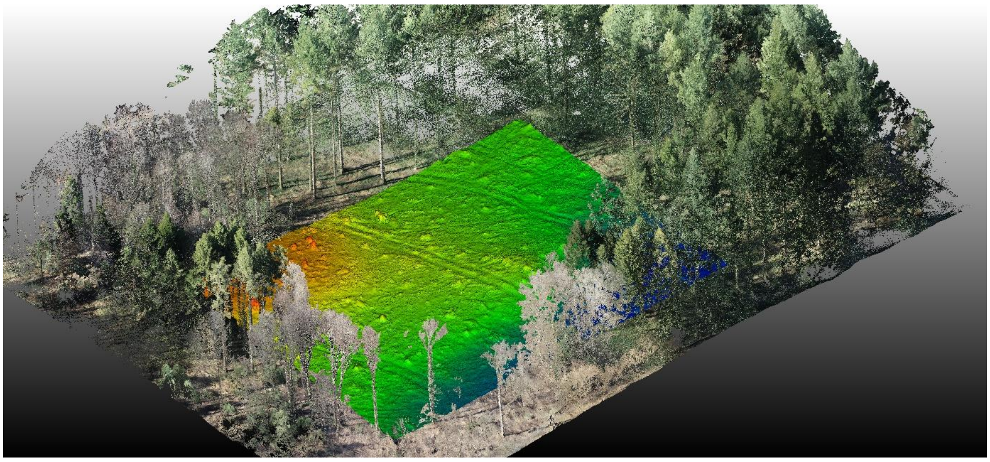

Figure 8: Example of LiDAR detection of soil compaction by machine traffic on skid trails (Griess/WSL).

Soil damage can also be prevented by appropriate working practices. Forestry tractors and skidders with winches have a great advantage on short passages where the ground carrying capacity is not sufficient for machine and load. They can lower the load without crossing the short section and then pull the load back towards them on more load-bearing ground. For forwarders, it is possible to drive with half the load if the damage potential is high. For cost reasons, however, this is only recommended to a very limited extent for a few trips.

2.2.7 Advantages of soil protection for the forest owner

The biggest advantage for current and future forest owners is that they will be able to achieve their silvicultural goals in a sustainable way without having to fear productivity losses due to soil compaction. They will have the necessary flexibility to adapt their fine development to the needs of future technical improvements and innovations. To conclude, with consistent planning and use of fine access, planning measures to avoid bottlenecks in the event of weather-related increases in soil moisture and a range of technical measures on harvesting machinery, the risk of soil damage can be contained.

2.3 Silvicultural measures

2.3.1 Silviculture

Silviculture is the study of the life history of forest trees. It aims to describe how trees species establish, grow, and respond in relation to site conditions, each other, and other organisms. Silviculture contributes to the knowledge foresters need to make the best possible decisions on how to manipulate forest stands for the certain and continuous production of goods and services desired from a forest. The application of silviculture is governed by three main principles.

- Trees grow and respond in ways that depend on ecosystems in which they grow; therefore, silviculture must be ecosystem-specific, i.e. tree species and site-specific.
- Ecosystems with similar characteristics will respond in similar ways to the same

manipulation; therefore, ecosystem classification is a tool for recognizing different ecosystems and applying different treatments.

- As forest growth cannot be fully controlled, a forester has to cooperate with nature; therefore, one must analyse and interpret each ecosystem to ensure that the management goals can actually be achieved under these conditions.

Thus, silviculture refers to the management of forest development through human intervention to achieve specific goals. It is the practice of controlling the growth, composition/structure, and quality of forest trees to meet values and needs. Although the traditional focus of silviculture was on timber production, modern silviculturalists take into account the society's often conflicting needs and demands about forests [1]. These refer to biodiversity and different providing (e.g. timber, water), supporting (e.g. nutrient cycle), regulating (e.g. carbon sequestration) and cultural (e.g. recreation) ecosystem services. An optimal provision of these functions requires adaptive management. This is further strengthened by climate change which can alter site properties such as climate, water supply, and the nutrient supply from soils (Jandl et al. [2]) and thereby alter tree species ranges and forest communities to species mixtures that are unfamiliar and unprecedented (O'Hara [4])).

2.3.2 Silviculture systems

A silvicultural system is a planned program of silvicultural treatments designed to achieve specific stand structure characteristics to meet site objectives during the whole life of a forest stand. This program of treatments integrates specific harvesting, regeneration, and stand tending methods to achieve a predictable yield of benefits from the stand over time. Silvicultural systems on most sites have been designed to maximize the production of timber crops. However, other non-timber objectives, such as avalanche control are common, too. Recently, ecological considerations and resource objectives have increased. Aspects related to biodiversity can be equally or more important than timber production. A silvicultural system generally has the following basic goals:

- provides for the availability of many forest resources (not just timber) through spatial and temporal distribution
- produces planned harvests of forest products over the long term, accommodates biological/ecological and economic concerns to ensure sustainability of resources
- provides for regeneration and planned seral stage development, effectively uses growing space and productivity to produce desired goods, services, and conditions
- meets the landscape- and stand-level goals and objectives of the landowner (including allowing for a variety of future management options)
- considers and attempts to minimize risks from stand-damaging agents such as insects, disease, and windthrow

2.3.2.1 Even- and uneven-aged stands

Even-aged stands generally have one age class, although two age classes can be found in some two-layered natural or managed stands. These stands generally have a well-developed canopy with a regular top at a uniform height. Pure even-aged stands generally have a nearly bell-shaped diameter distribution. This means that most trees are in the average diameter class. However, diameter distributions should be viewed cautiously since diameter can be a poor criterion for age. The smallest trees in natural even-aged stands are generally spindly, with vigour suppressed by the overstorey.

In contrast, uneven-aged stands have three or more well-represented and well-defined age classes, differing in height, age, and diameter. Often these classes can be broadly defined as regeneration (perhaps regeneration and sapling), pole, and sawtimber (perhaps small and large sawtimber). In the classic managed form, where diameters are a good approximation for age, distribution of diameters will approach the classic inverted-J form. The objective of such an approach is to promote sustained regular harvests, with short intervals, at the stand level. Uneven-aged stands have an uneven and highly broken or irregular canopy (often with many gaps). This broken canopy allows for greater light penetration and encourages deeper crowns and greater vertical structure in a stand.

A sample list of silvicultural systems in correlations with the ecological needs of the main commercial tree species can be found in Table 1. For the purpose of this deliverable, we are going to focus on the two silvicultural systems that are in use at demonstration sites in Finland and Switzerland, i.e. the clearcut- and the selection system (see section below).

Silvicultural system	**Ecolog. tree type**	**Main target tree species**
Clear cut	Pioneer	Betula spp., Populus spp., Alnus spp., Salix spp., Pinus sylvestris, Larix decidua
Gap/strip cuts	Intermediate	Picea abies, Fraxinus excelsior, Acer pseudoplatanus, Acer platanoides, Acer campestre, Quercus petraea, Quercus robur, Prunus avium
Uniform shelterwood	Intermediate – late successional	Fagus sylvatica, Tilia spp., Carpinus betulus
Group shelterwood	Late successional	Abies alba, Fagus sylvatica, Picea abies
Selection		Albies alba, Fagus sylvatica

Table 1: Selected silvicultural systems in correlations with the ecological needs of the main commercial tree species.

The Clearcut System. The clearcut system manages successive even-aged stands by cutting the entire stand of trees at planned intervals then regenerating and tending a new stand in place of the old.

The Selection System. The selections system is used by Stephan Haab to manage the forest stands in the Swiss project region. Selection systems remove mature timber either as single scattered individuals or in small groups at relatively short intervals, repeated indefinitely, where an uneven-aged stand is maintained. Regeneration should occur throughout the life of the stand with pulses following harvest entries.

In both cases, systems depend on recruitment of trees into successive age classes over time and the predictable yield from merchantable age classes. Yield will be obtained by thinning clumps, by harvesting individual trees, or by harvesting whole groups of the oldest age class to create small openings scattered throughout the stand.

The selection system can be complex. Adding to the complexity of the system are the, in the timeframe of a tree, rapidly changing climatic conditions. The Decision Support System will help the forester of the Swiss Case study site, Stefan Haab, to tackle that complexity and adapt his management decisions.

3 Part C: Labels

To monitor timber and other management goals, criteria and indicators are defined for a spectrum of forest outputs and conditions, ranging from maintaining biological diversity to maintaining economic viability. This scope introduces complexity beyond what a single model or a single forester can easily manage. A team of experts is required to provide both the modelling skills and the scientific credibility necessary to cover the scope of timber and non-timber outputs. Expertise is needed in stand-level modelling, harvest scheduling, hydrology, biological diversity, forest ecology, forest operations, economics, recreation, visualization, and sociology. This team will use a suite of models to formulate and explore questions at various temporal and spatial scales. Rather than building one monolithic model, the team designs a Decision Support Systems with individual models and the necessary linkages for exchanging inputs and outputs. Some portions of the forest estate are typically more contentious than others when it comes to managing timber and non-timber outputs. These compartments may require tactical and even operational plans to supplement the strategic planning process. Therefore, a Decision Support Systems is needed. It must be flexible enough to accommodate the different data and modelling demands at each level of the planning hierarchy.

In the following section, a brief overview is given showing which labels are most relevant to be collected. With the aid of these labels, many variables can be derived or calculated that are crucial for proper forest planning and serve as input for Decision Support Systems. This part is work in progress and will be published as peer-reviewed paper.

3.1 Labels with a 1-1 relation

3.1.1 Height

Highest point of main vertical axis or distance between ground points surrounding (elaborate) stem and highest point (Figure 9). Tree height is an important value that is needed to assess site quality. It is also needed in all volumetric calculations for stem and crown.

3.1.2 Wooden structure

Point that could be identified by colour as part of the wooden structure of the tree (Figure 10).

The label is the basis for all structural sub-labels of the tree.

3.1.3 Leaf

Point that could be identified by colour as part of the crown of the tree (Figure 10). The label leaf is the basis for all sub-labels that focus on the crown. The development of the crown has a strong correlation with the growth potential of a tree, its social status within a cohort, its vitality and many more.

3.2 Labels with a 1-n relation

3.2.1 Tree species

Indicates the common and Latin name of the tree. Common names often vary from country to country, even when they share the same language. We still should include both to tend to the needs of all stakeholders involved in the decision-making process.

3.2.2 Based on 1-1 label leaf

3.2.2.1 Live Crown Ratio

The live crown ratio (LCR, equation 1) is a good indicator of the vigour of a tree, its shade tolerance and crown class. It is the ratio of crown length to total height; expressed as a percentage. The crown length is defined as the distance from the top of the tree to the lowest limb with green leaves (Figure 11).

$$\text{Live Crown Ratio} = \frac{\text{length of crown}}{\text{tree height}} * 100 \tag{1}$$

3.2.2.2 Crown volume

The crown volume (Figure 12) is similar to the live crown ratio an important factor to assess the vigour of a tree and its place in the social structure. There is an established empirical correlation between crown volume and tree biomass. For the practitioner knowledge of the crown volume plays an important rule to create per-commercial and commercial thinning prescriptions. It is defined as the volume of a mesh tightly wrapped around the crown. The solid body that is created has a length corresponding with the label length of the live crown and the crown projections.

3.2.3 Social structure

The social structure (Figure 13) is a concept that allows the forester to create management plans for certain cohorts within a forest stand. In an even aged stand, he would promote the best dominant trees by allocating more nutrients and growing space. In order to accomplish that he would, in certain intervals, remove the nearest dominant or co-dominant or neighbour to give the crown space to grow into, and remove trees from the intermediate and suppressed cohort to reduce competition for nutrients.

3.2.4 Based on label woody structure

3.2.4.1 Diameter breast height

Diameter at breast height is the measured of the tree's trunk diameter at 1.3 m above the point of germination (Figure 14). The DBH is correlated to other growth and volume calculations and characteristics of a tree.

3.2.4.2 Clear wood

Clear wood is the part of the stem with no visible limbs (Figure 15). It has the highest value of the round wood sorts generated from the merchantable volume of the stem.

3.2.4.3 Merchantable volume

Merchantable Volume is the gross volume of the stem, in cubic meters, between two distinct heights (Figure 16). The locations of the felling cut and the cut to remove the treetop. The felling cut is located as low as possible to maximize volume in the area with the highest monetary value. The cut off height for the treetop is defined by a minimum diameter. This diameter is variable and depends on a variety of factors that will need to be optimized in the Decision Support System.

3.2.4.4 Tree structure

The tree structure (Figure 17) consists of four sub-labels of the main label wooden structure. The tree structure is the basis for the quality assessment of a tree and thus for the management decisions the forester must make.

- The stem is the principal axis of a tree from which buds, shoots and limbs develop
- Limbs are the primary division from the stem
- Branches are primary divisions from the limb
- Twigs are primary divisions from the branches

3.2.5 Quality assessment wooden structure

3.2.5.1 Stem defects

In a forest that is managed to generate resources for the wood products industry a certain minimum quality, in accordance with the industry standards, must be maintained. Stems of the highest quality are straight, have a long knot free section at the bottom and long distances between the whirls. In a forest that is managed for biodiversity defects are often the starting point in the creation of microhabitats.

3.2.5.2 Bends

Bends are defined as any deviation from a straight main axis of a tree (Figure 18). Bends can occur i.e. when the main axis of the tree breaks off and a limb takes over as the new main axis.

3.2.5.3 Pistol grip

The pistol grip is a unique bend that has its roots in external factors. It occurs mainly on slopes where the snow cover slides down on a grass mat in early snow melt conditions and bends the young tree repeatedly off its natural position (Figure 19).

3.2.5.4 Biodiverstiy/ Microhabitats

A defect viewed from a commercial standpoint but also an important microhabitat (Figure 20, Figure 21). Tree cavities and hollows are a key structural components to increase habitat suitability for certain bat species at risk.

The crack in the tree created by a lightning strike can be an excellent bat habitat (Figure 21).

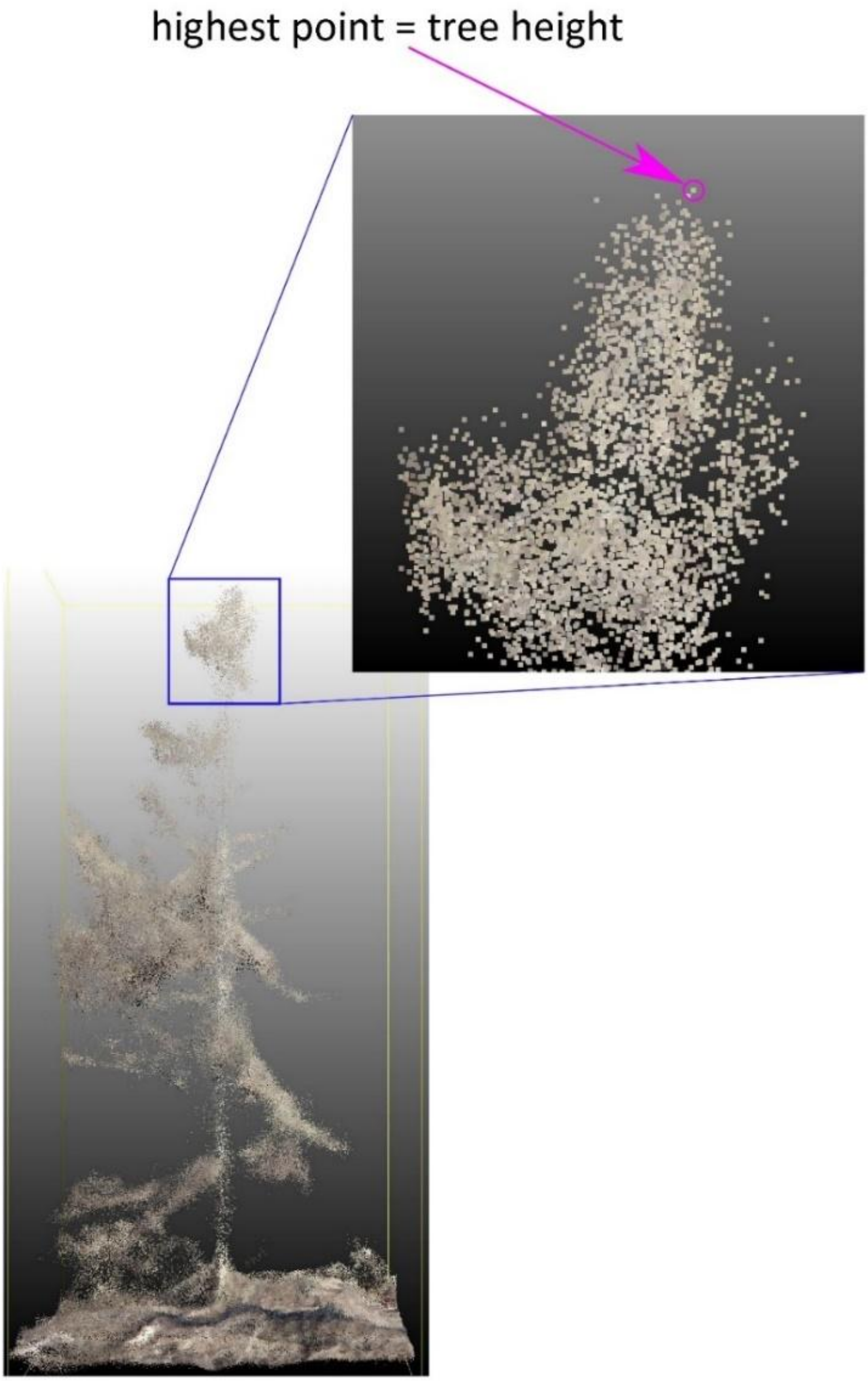

Figure 9: Demonstration of highest point of main vertical axis or distance between ground points surrounding stem and highest point (Griess/WSL).

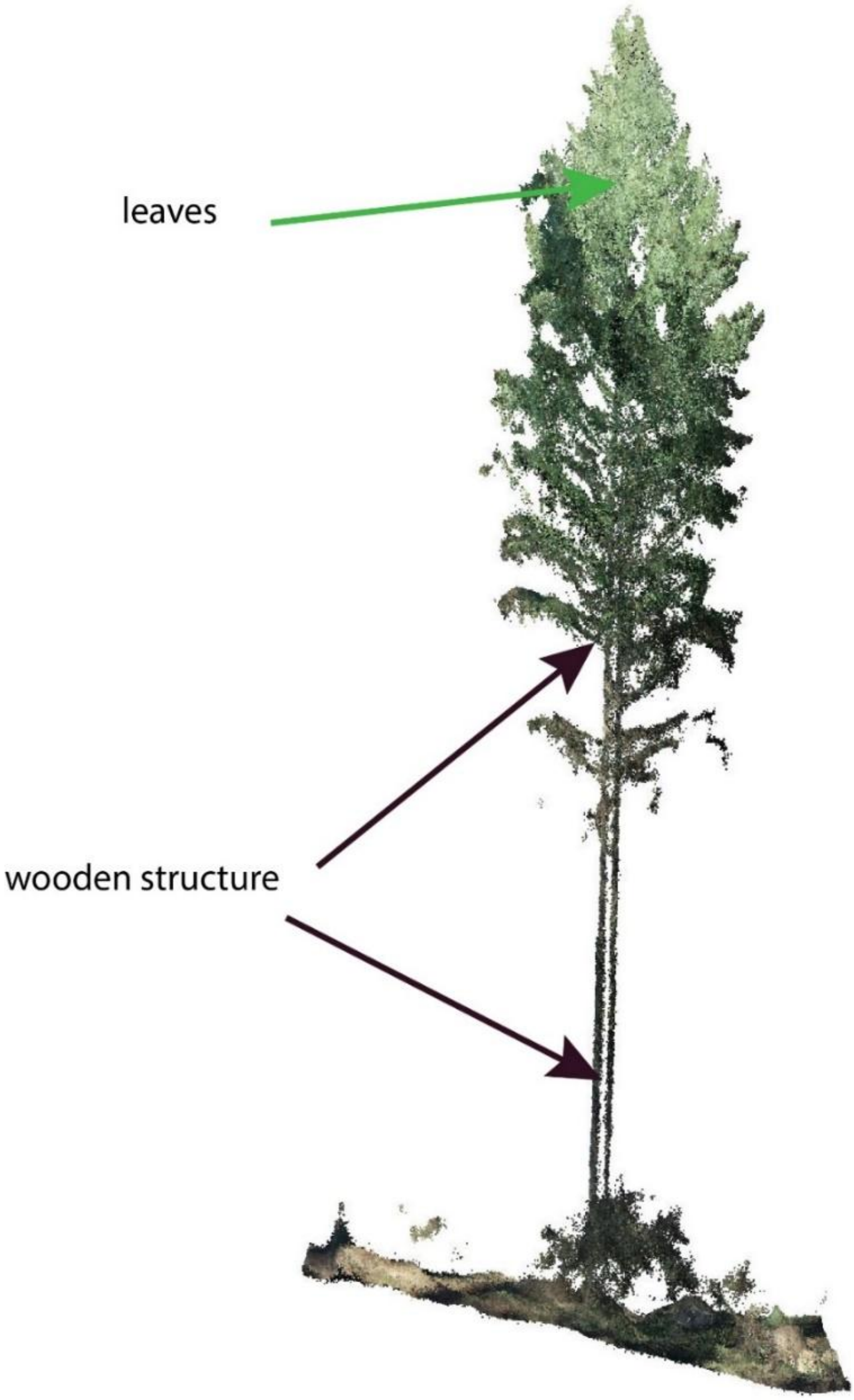

Figure 10: Labels for the basic above ground structure (Griess/WSL).

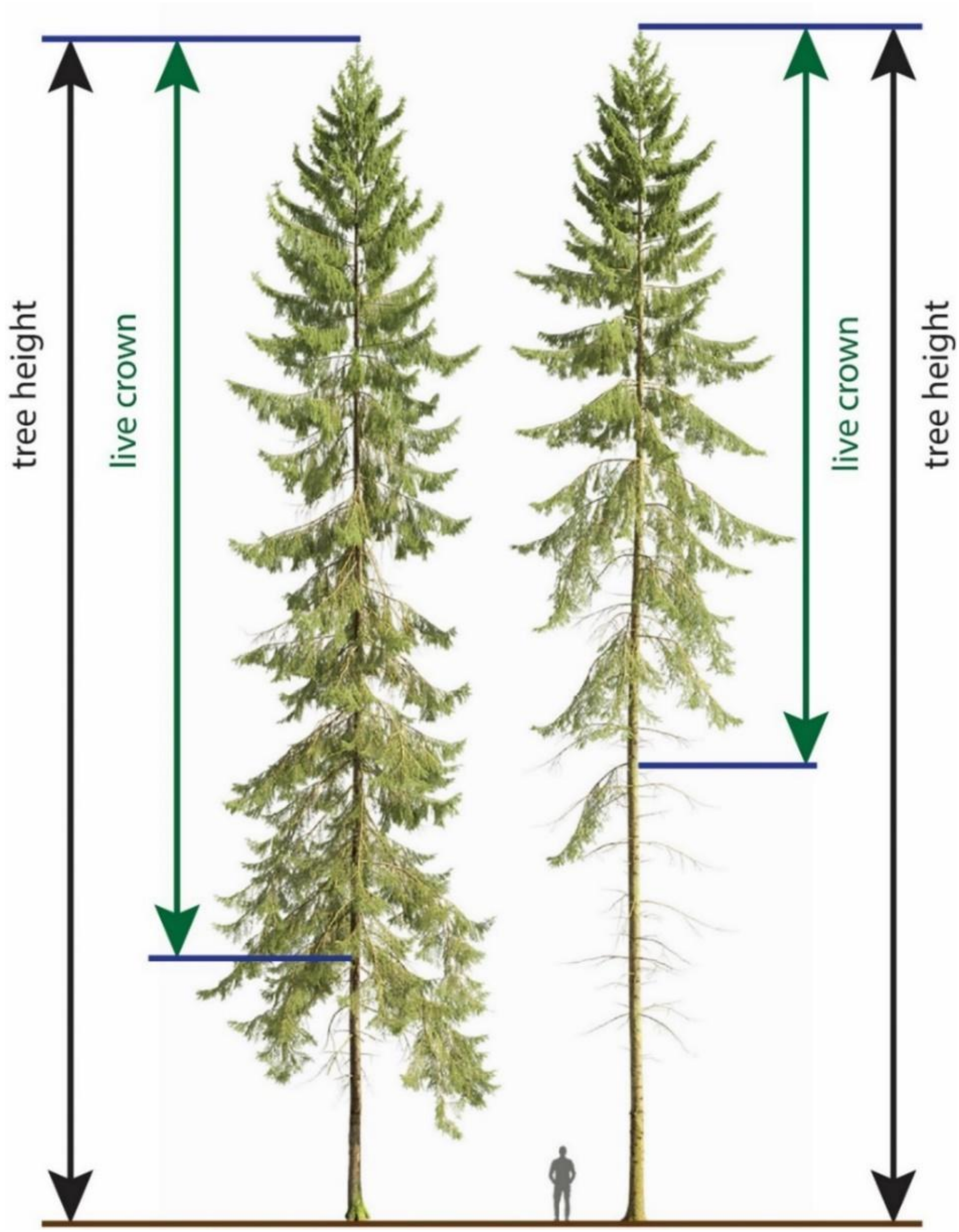

Figure 11: Label live crown ratio (Griess/WSL).

Figure 12: Label crown volume (Griess/WSL).

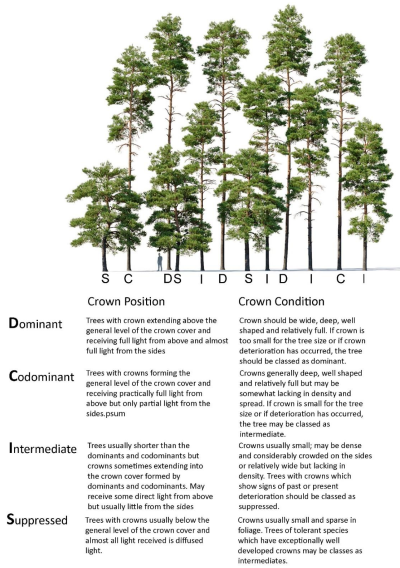

Figure 13: Social structure of trees in a forest stand (Griess/WSL).

Figure 14: Label Diameter at Breast Height (DBH) (Griess/WSL).

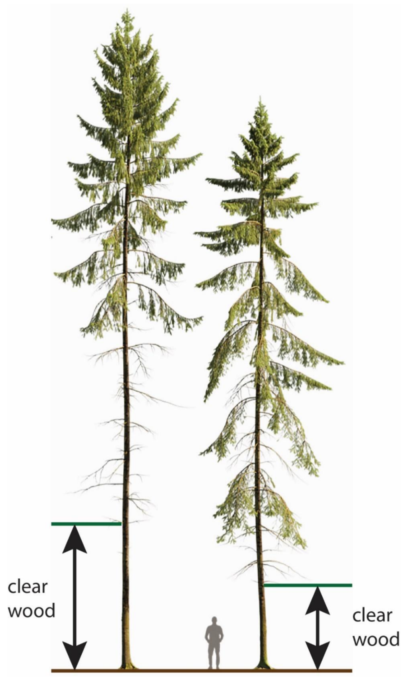

Figure 15: Label clear wood (Griess/WSL).

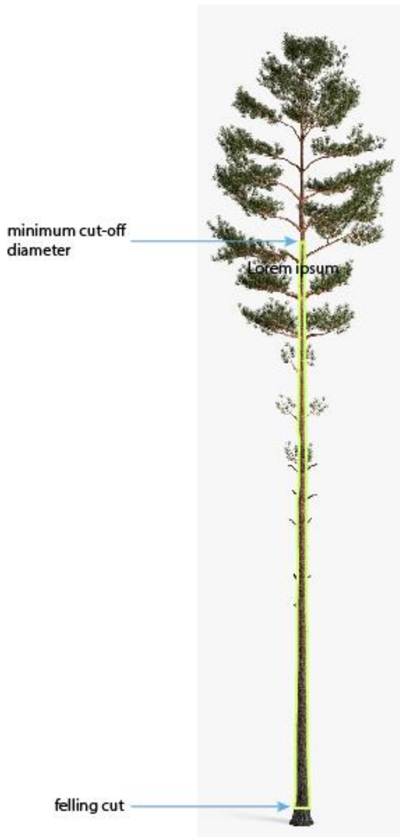

Figure 16: Label merchantable volume (Griess/WSL).

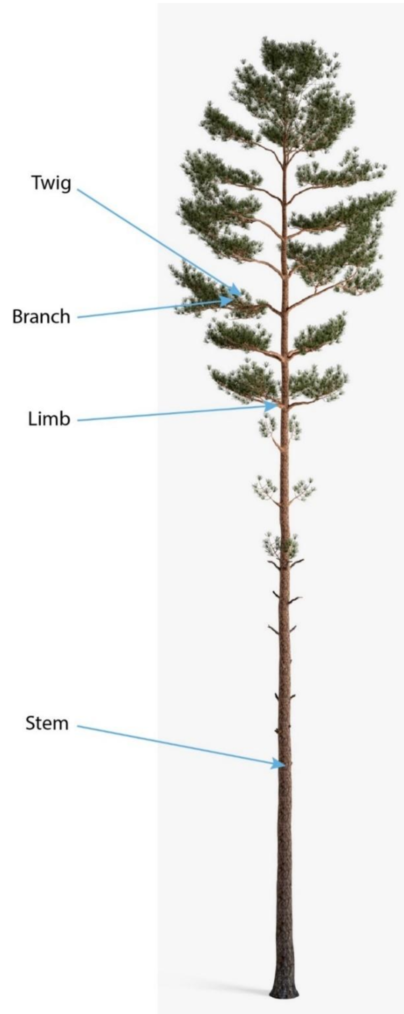

Figure 17: Label tree structure (Griess/WSL).

Figure 18: Label bends (Griess/WSL).

Figure 19: Pistol grip (Source: http://www.fotogalerien.ch).

Figure 20: Cavity at the bottom of a tree (Griess/WSL).

Figure 21: Crack in a tree struck by lightning (Source: https://www.feuerwehren-stadt-bleckede.de).

References

[1] Jeffery Burley. *Encyclopedia of forest sciences.* Academic Press, 2004.

[2] Robert Jandl et al. "Forest adaptation to climate change—is non-management an option?" In: *Annals of forest science* 76.2 (2019), pp. 1–13.

[3] Peter Lüscher et al. "Physikalischer Bodenschutz im Wald". In: (2019).

[4] Kevin L O'Hara. "What is close-to-nature silviculture in a changing world?" In: *Forestry: An International Journal of Forest Research* 89.1 (2016), pp. 1–6.